Advanced Communications Technologies in Support of NASA Mission

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The NASA John H. Glenn Research Center at Lewis Field

Outline of Presentation

- Importance of Communications
- Existing and Proposed Communications Networks
- Communications Technologies
- Communications Technology Development at Glenn Research Center
- Summary

Importance of Communications

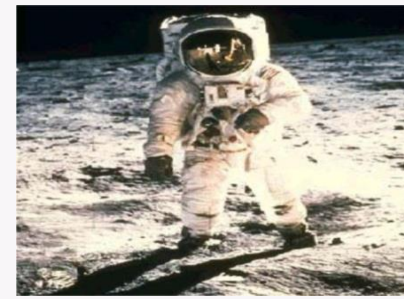
Ground Control

Robotic-based Exploration

Human-based Exploration

Spacecraft/Satellite Exploration

Aircraft/Airborne Platform



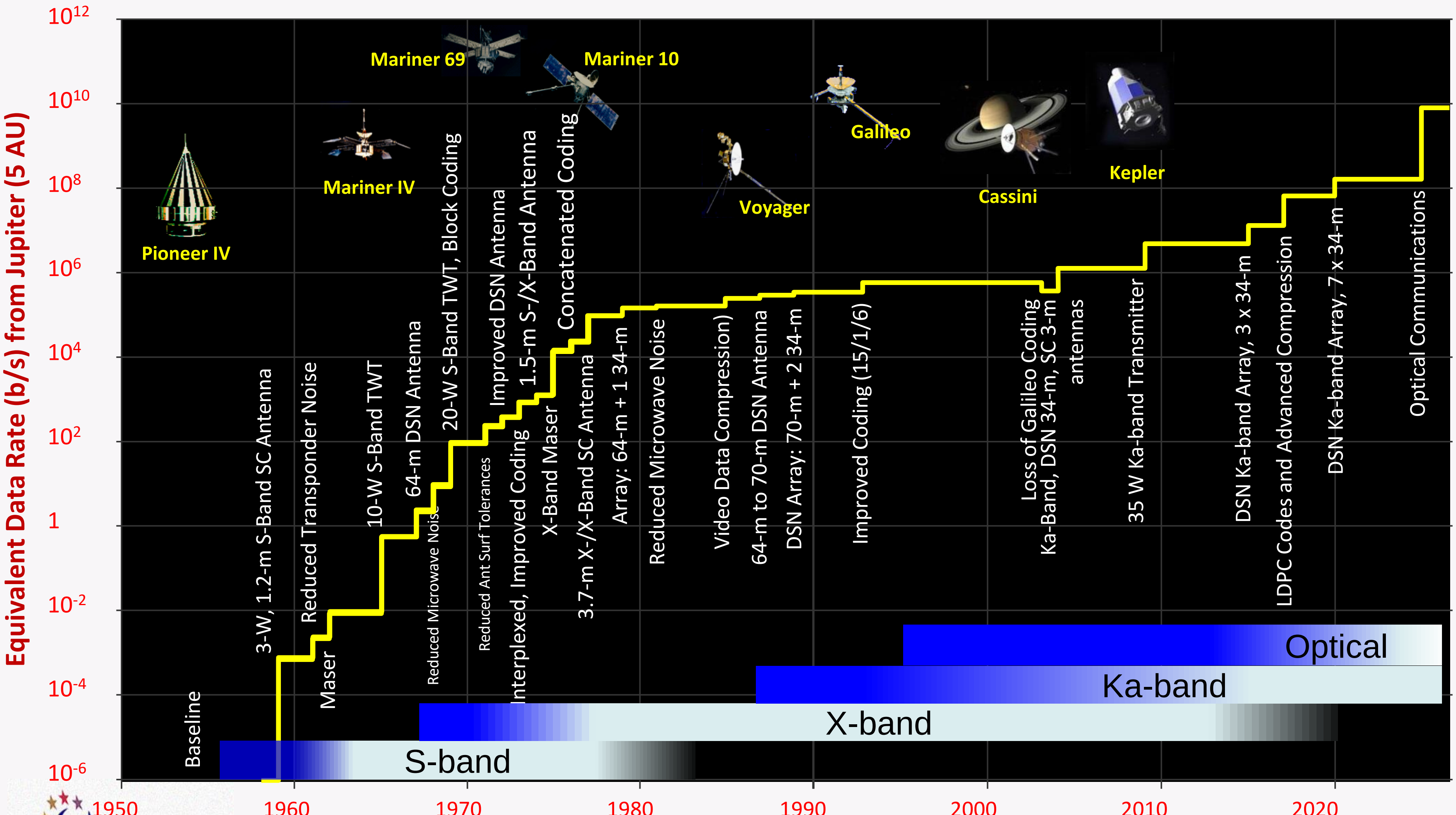
Enable Forward/Return Communications and TT&C with:

- Humans in the space environment
- Spacecraft
- Planetary Surface (e.g., Rovers)
- Aircraft and other airborne platforms

Primary Goal in Space to Earth Communications

"Increase Data Rate and Throughput"

Deep Space Communications Downlink Data Rate Evolution



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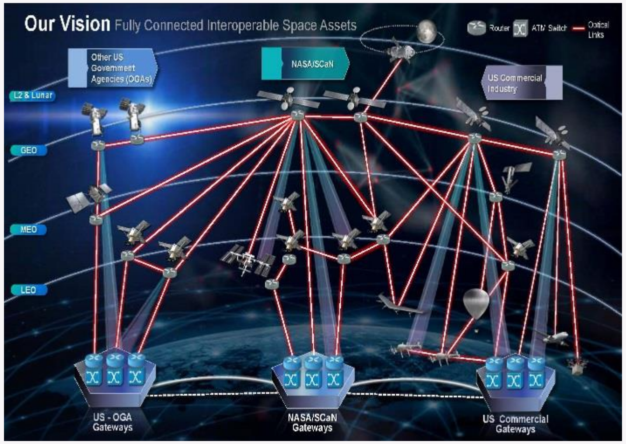
[Ref. J. H. Yuen; https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter1--141029.pdf]

Existing and Proposed Communications Networks

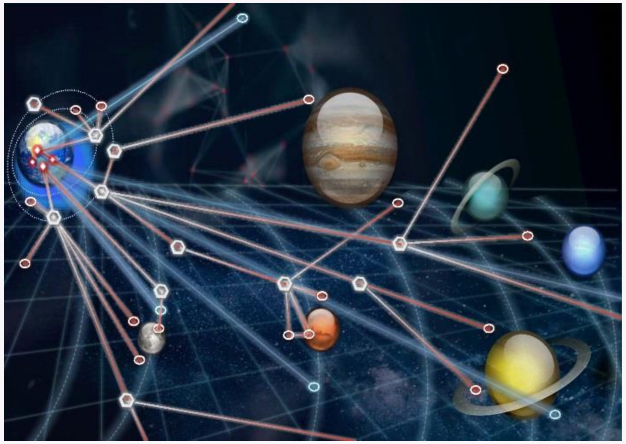
Space Communications and Navigation (SCaN) Operational Network

Space Communications and Navigation Decade of Light Vision

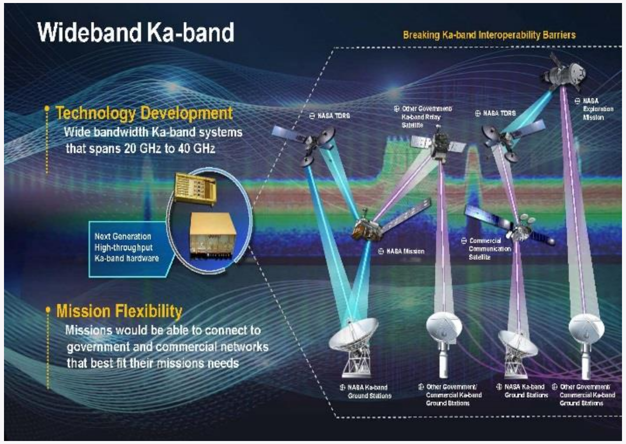


SCaN Next Generation Architecture

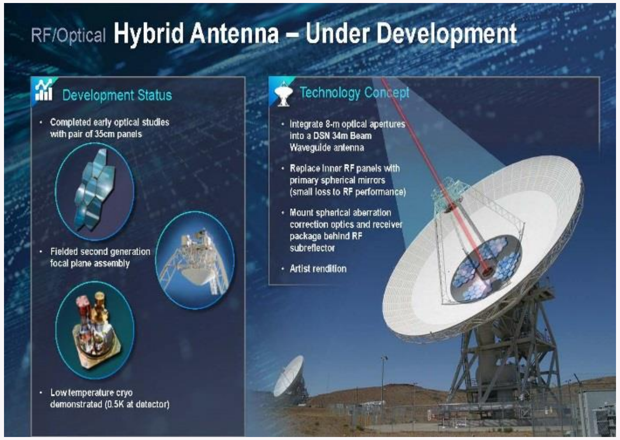
Optical & Ka-Band
Disaggregated
Software Defined
Multi Node
Networked
Delay/Disruption Tolerant
Autonomous
Interoperable
Affordable
Extensible

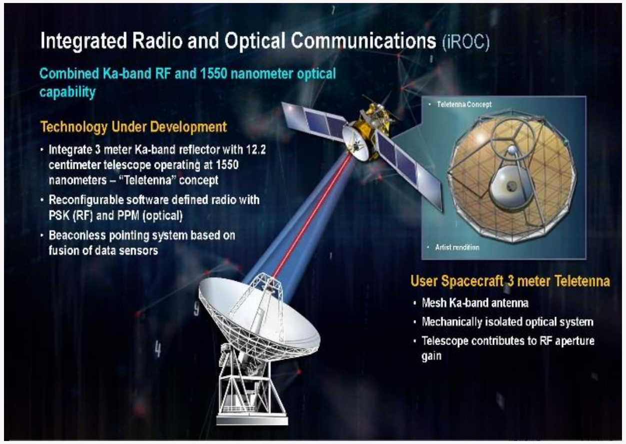


SCaN Interplanetary Network



Breaking Ka Band Interoperability Barriers





Hybrid Radiofrequency Optical Technology – Under Development

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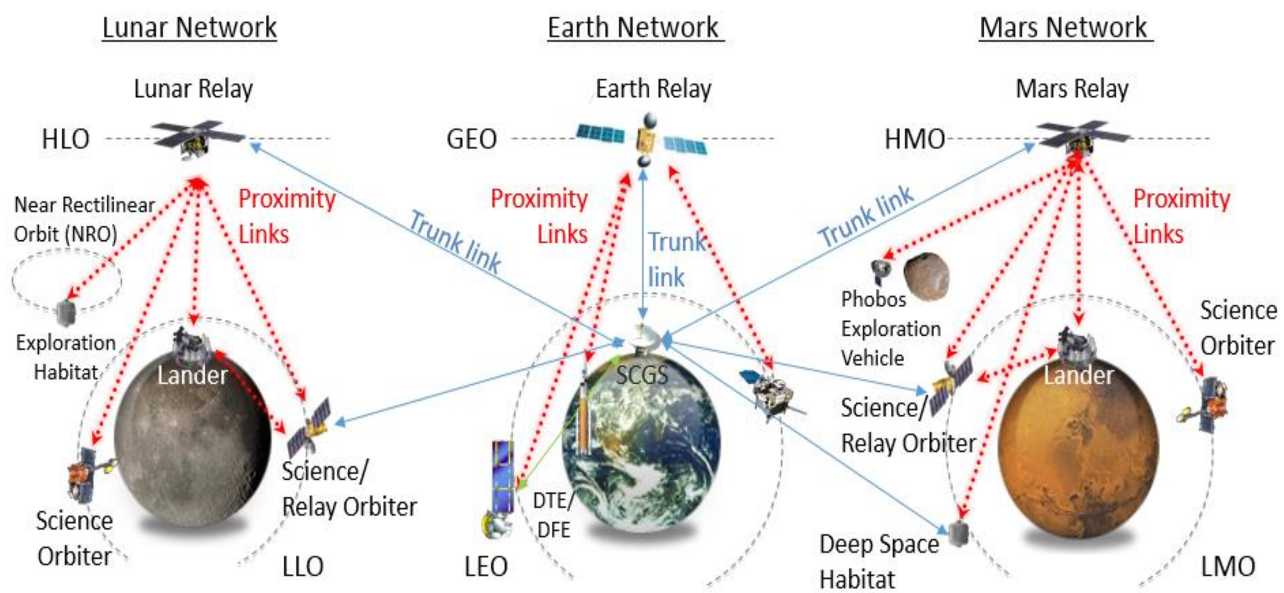
Future Space Communications and Navigation Architecture

Time to update both Near Earth and Mars Relay satellite infrastructure

- Near Earth TDRS are nearing their design lifetime…expected to retire TDRSS by 2025 timeframe
- Mars relays satellite (e.g., MRO) expected to reach end of life in 2025 timeframe

Human exploration of Mars requires look at current and updated Mars infrastructure

Future Communications System Architecture spans 2025 to 2040+



Benefits of Planetary Networks:

- **Reduced mission burden with short links for in-system communications - enables in-system telerobotics**
- **Common architecture reduces technology & development costs**
- **Reuse of HW & SW: Family of products includes variants for different environments**
- **Reuse of spectrum**

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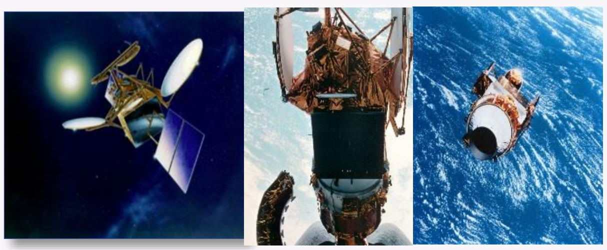
GRC's Space Communications Platforms

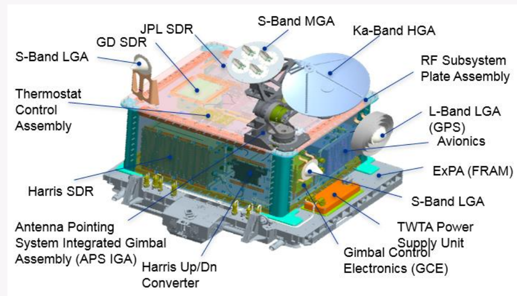
Advanced Communications Technology Satellite (ACTS) (1993-1997)



Industry Focused
- Switchboard in the Sky
- Spot Beaming
- Processing
- Aircraft Sat Communications
- Enable Space Internet

Demonstrated suitability of Ka-Band frequencies For Space Communications

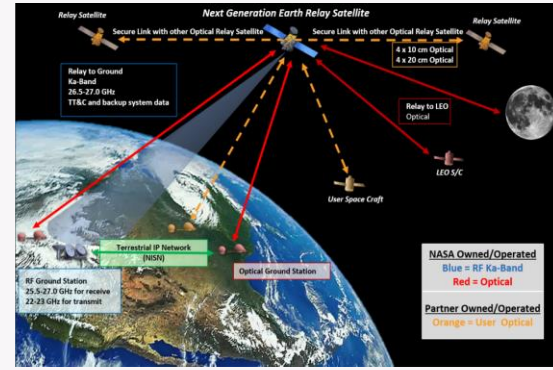
Space Communications and Navigation Test Bed (STB) (2012-2018)



Scan Testbed Flight Radio Experiments and Demonstrations
- GPS Navigation and Timing
- Ka-Band, Bandwidth-Efficient, High Rate Waveform
- S- and Ka-Band IP Networking and Routing
- Adaptive Modulation and Coding for Cognitive Radio

Demonstrated Suitability of Software Defined Radio (SDR) for Space Communications

Next Generation Optical Relay Concept (Being Proposed)



- First Node Next Generation Architecture
- Public Private Partnership (PPP)

Enables US Commercial End to End Optical Communications

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To enable these Communications Networks we need Communications Technologies

SCaN Technology Development Roadmap

GRC Space Communications Technology Summary

GRC's Mission: We drive research, technology, and systems to advance aviation, enable exploration of the universe, and improve life on Earth.

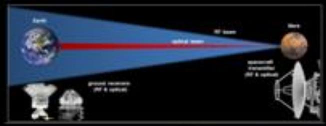
- Provide world-class research and technology, revolutionizing aeronautics and space exploration.
- Advance space missions and aeronautics by leveraging our core competencies to deliver from concept through applications

Today's Communications Spaceflight Projects and Technology Development

Space Communications & Navigation (SCaN) Testbed

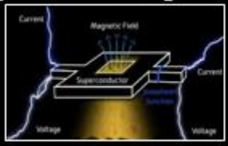
Next Generation SCaN Architecture

Integrated Radio and Optical Communications (iROC)



Space Communications Research & Technology

- Quantum Communications
- High Temperature Super Conducting Communications
- Modeling & Simulation
- Delay/Disruption Tolerant Networking
- Antenna Design and Testing



Space Communications and Navigation (SCaN) Projects

- Software-defined radios (SCaN Testbed)
- Cognitive Communications
- RF propagation and RF/optical hybrid technology
- Network Services Compatibility Test Sets
- Program Systems Engineering
- Spectrum Management

GRC's Communications Spaceflight Heritage

Communications Technology Satellite (CTS)

Advanced Communications Technology Satellite (ACTS)

GRC's Contributions in Ka-Band Technology

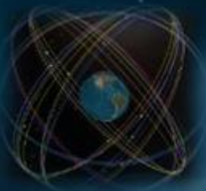
GRC Pioneered Ka-Band Travelling Wave Tube Amplifiers and Ka-Band MMIC Devices

CTS TWT Cross Section

LRO 40-W K-Band TWT & Electronic Power Conditioner

Ka-band GaAs Monolithic Microwave Integrated Circuit

GRC is a Leader in RF Propagation and Spectrum Management



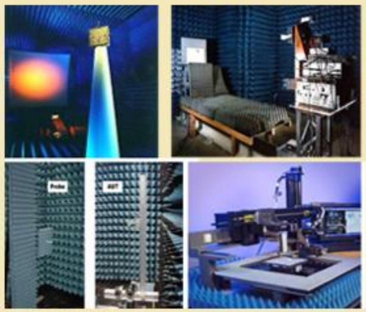
Spectrum Management

Propagation terminals around the world

RF Communications Technology

Antenna Technology

Antenna Metrology Facilities



- *Far Field Range*
- *Near Field Range*
- *Compact Range*
- *Near Field Cylindrical Range*
- *Antenna Near Field Planar Scanner*

Aerospace Communications Facility (ACF)
(expected in place circa 2021)

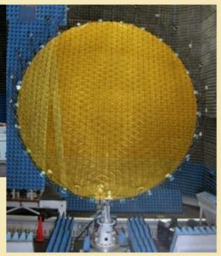
Receiver at University of Alaska Fairbanks (UAF)

Large Aperture Antennas

4 x 6m Aperture Inflatable Antenna

BB2.5 Radome Antenna

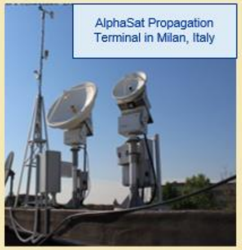
3.2 m Shape memory Polymer Composite Reflector



NGST 5 m "Astromesh" Reflector in NASA GRC Near-Field Range

(Circa 2004-2009)

GRC Advanced Ka- and Q-Band Ground Terminals



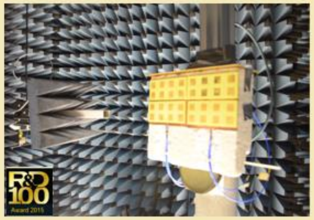
(Circa 2014)

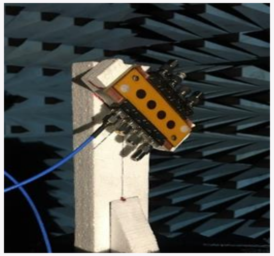
Aerogel Antennas

Conformal Lightweight Antenna Structures for Aeronautical Communication Technologies (CLAS-ACT):

Goal: Develop conformal aerogel antenna element and subarray to reduce SWaP in UAV SatComm Systems

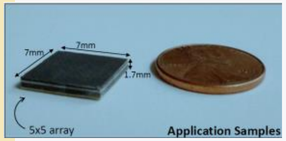
(Ongoing)

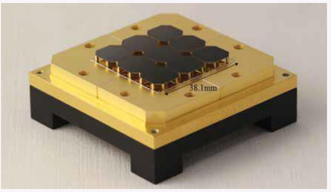




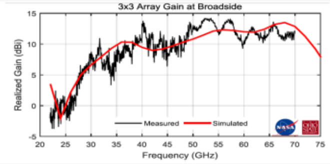
CLAS-ACT 4 Element Sub-Array Antenna on Aerogel Substrate in Test Range:

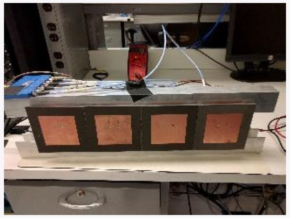
Ultrawide band antennas





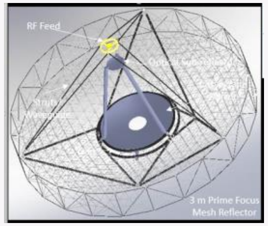
WISM demonstrates 8-40 GHz operation (Nuvotronics, Inc.) Outer dimensions of the antenna are 71.1mm by 71.1mm, although the PolyStrata® portion is 38.1mm on a side.





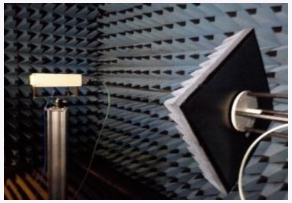
GPS L5 Phased Array developed for the Terrain Imaging

Teletenna for iROC

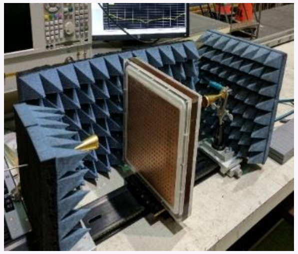


3D Printed Antennas For SmallSat & UAS applications

Switched Array
360° Az, 30° El Coverage
Collaborative effort with UTEP, UNM, and COSMIAC



Kymeta Antenna in Cylindrical Near Field Range



CIF SS under Test

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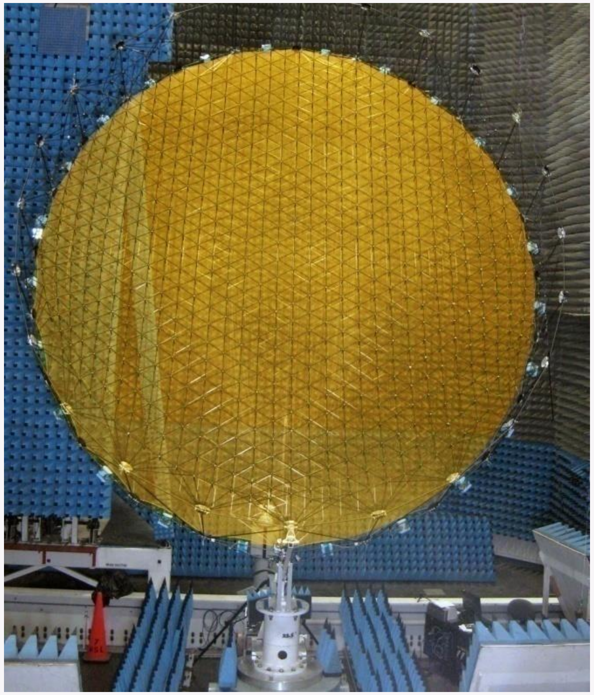
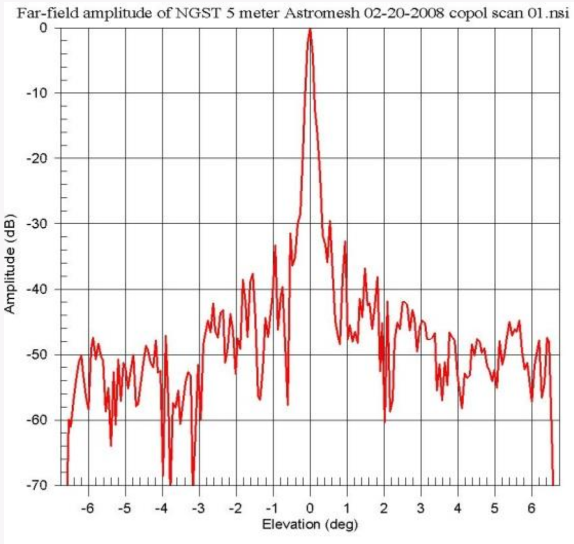
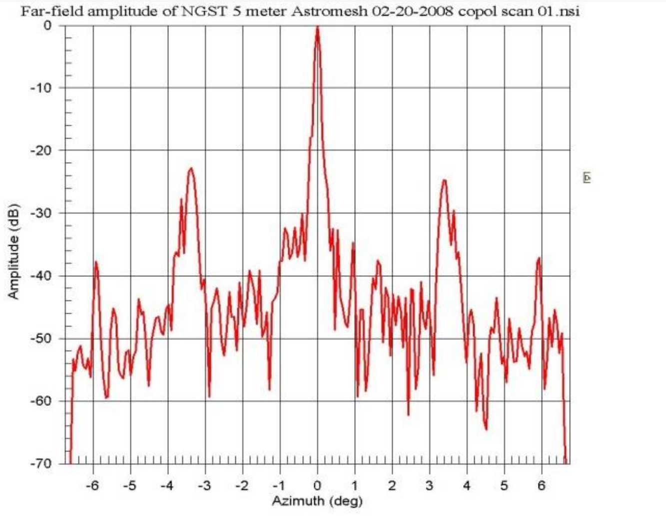
Mesh Reflectors

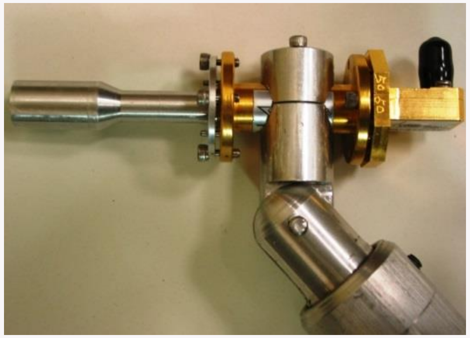


NGST 5 m “Astromesh” Reflector in NASA GRC Near-Field Range. The reflector was evaluated at 32, 38, and 49 GHz as well as a laser radar surface accuracy mapping.





Far Field Elevation and Azimuth pattern at 33 GHz (Directivity = 62.8 dB)



GRC Dual-band feed horn assembly

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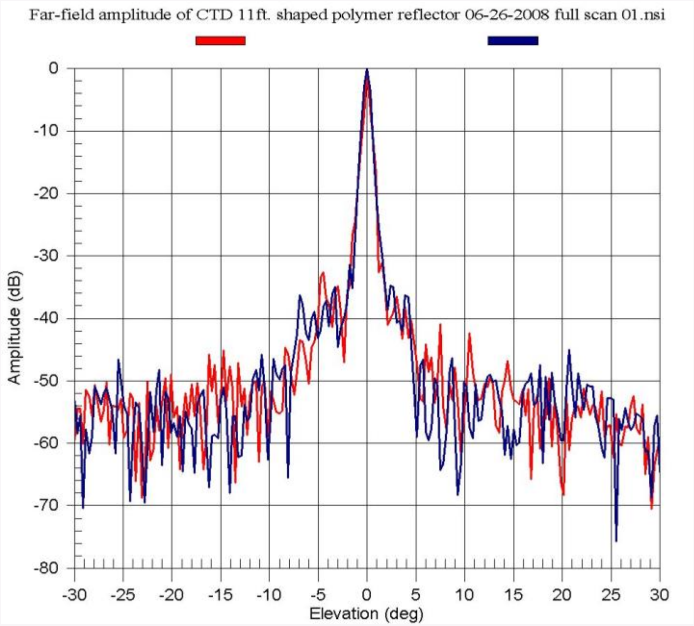
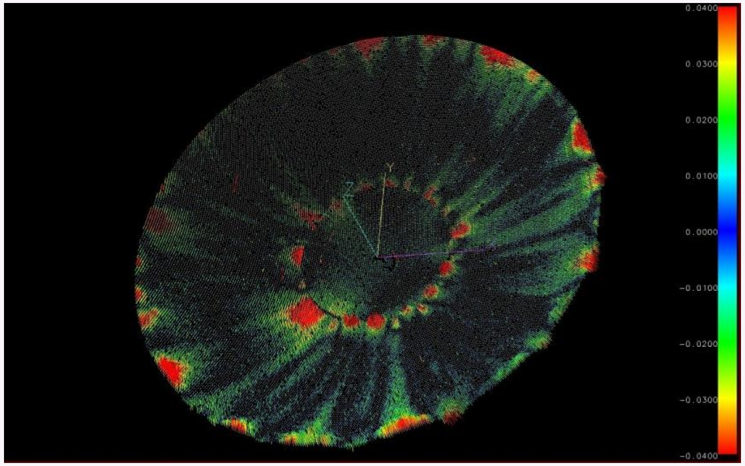
Shape Memory Polymer Reflector

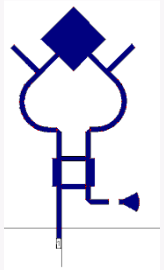
Composite Technology Development 3.2 m Shape Memory Polymer Composite Reflector at GRC Near Field



Far-field pattern at 20 GHz. Directivity = 50.3 dB (aperture was severely under-illuminated)



Surface metrology based on laser radar scan. RMS error=0.014”



Initial 20 GHz Microstrip Patch Feed (length is 0.620”)

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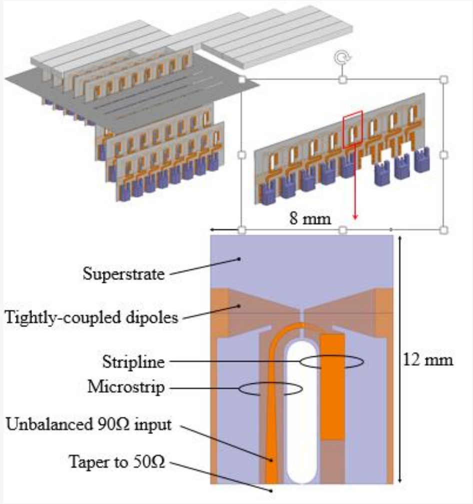
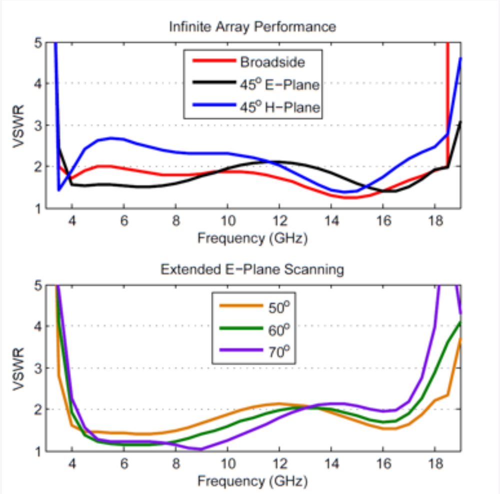
Miniature, Conformal and Spectrally Agile Ultra Wideband (UWB) Phased Array Antenna for Communication and Sensing

(Collaborative effort between OSU and GRC)

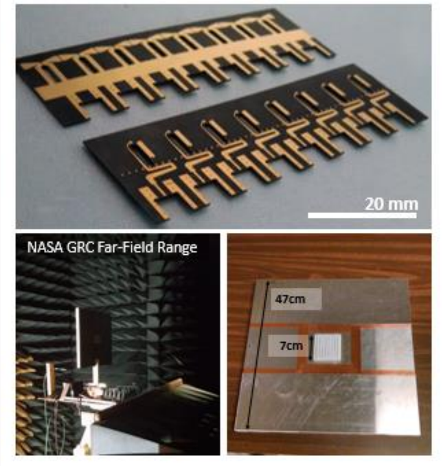
Tight Coupled Dipole Array (TCDA)



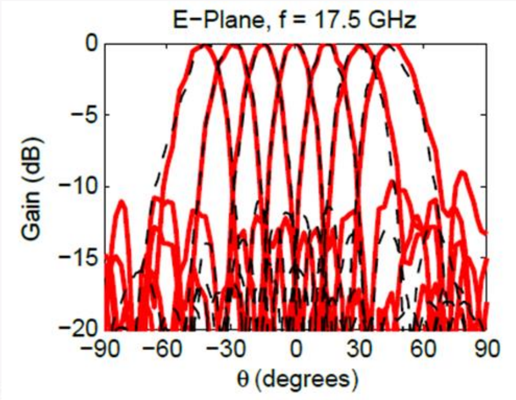
Simulations

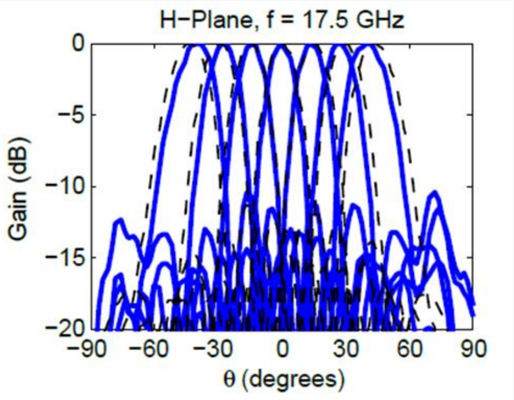


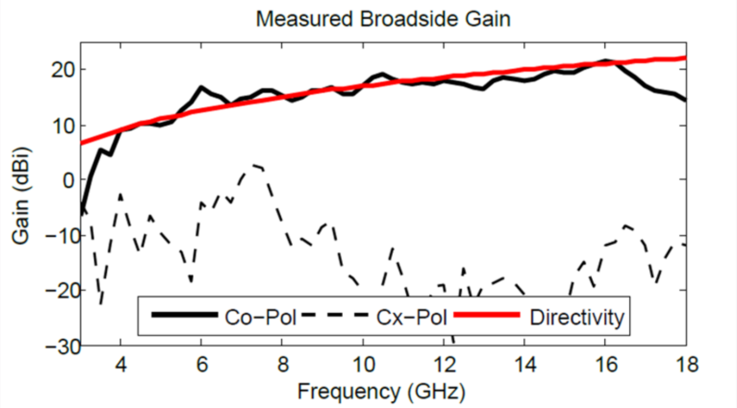
TCDA Fabrication and Characterization



Experimental Results







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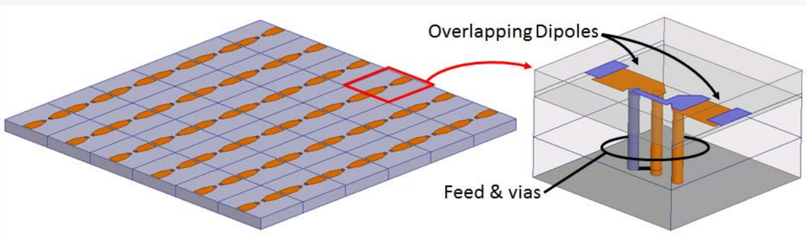
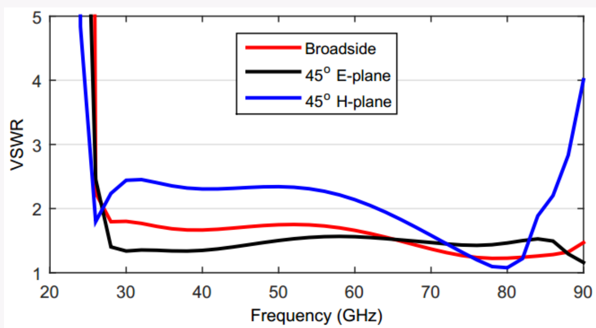
Ref: "Wide Band Array for C-, X-, and Ku-Band Applications with 5.3:1 Bandwidth," Markus H. Novak, John L. Volakis, and Félix A. Miranda, 2015 International Symposium on Antennas and Propagation, July 19-25, 2015, Vancouver, CANADA

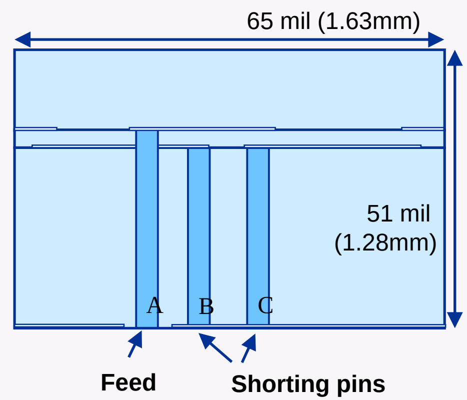
Miniature, Conformal and Spectrally Agile Ultra Wideband (UWB) Phased Array Antenna for Communication and Sensing

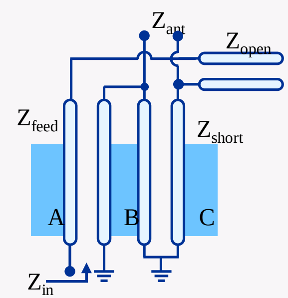
(Collaborative effort between OSU and GRC)

Planar TCDA for Millimeter-Wave Applications









- 26 GHz–86 GHz with VSWR<1.8 at broadside
- Min. feature size: 3 mil (76um)
- Designed for PCB fabrication

Ref: “Low Cost Ultra-Wideband Millimeter-Wave Array,” Markus H. Novak, John L. Volakis, and Félix A. Miranda, 2016 International Symposium on Antennas and Propagation, Fajardo, Puerto Rico.

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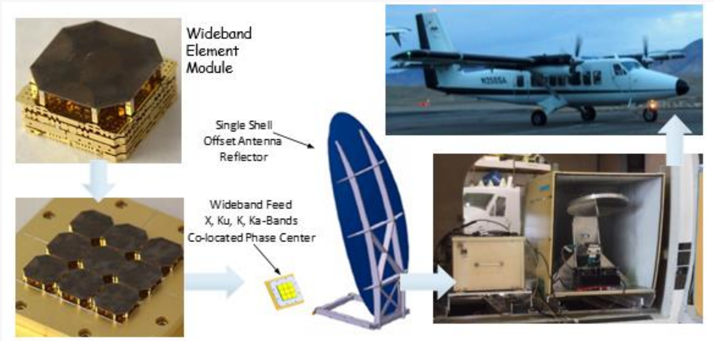
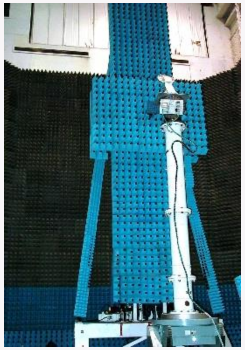
Wide Band Antenna for Wideband Instrument for Snow Measurements (WISM)

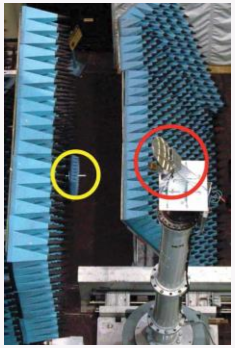
Reflector System Integration, alignment and Characterization



Enabled by advanced CSA technology, WISM is a new broadband multi-function research instrument for NASA's snow remote sensing community

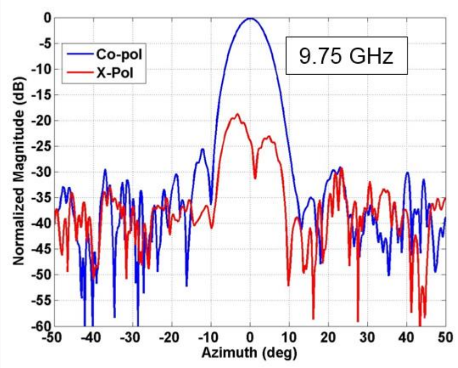


Antenna and vertical scanner of GRC Near Field Range .

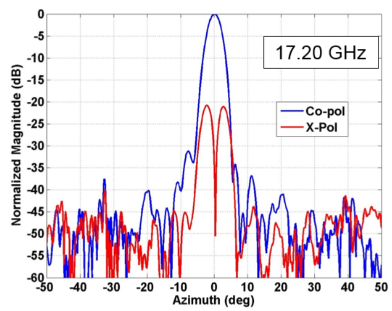


Top view of antenna and near-field probe.

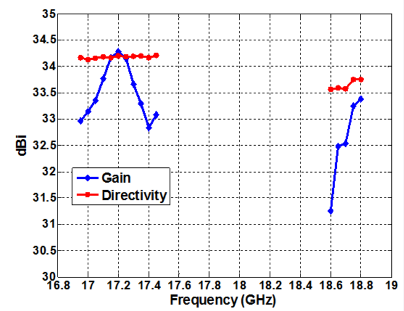
Principal Plane Pattern

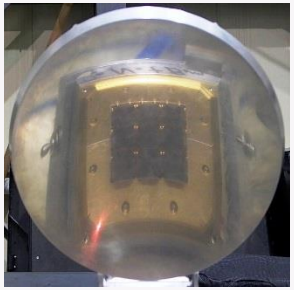


Principal Plane Pattern



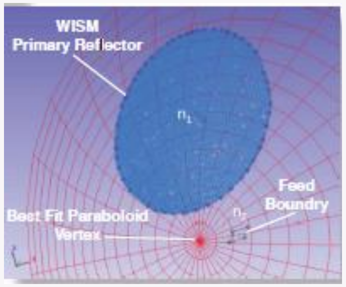
Directivity and Gain





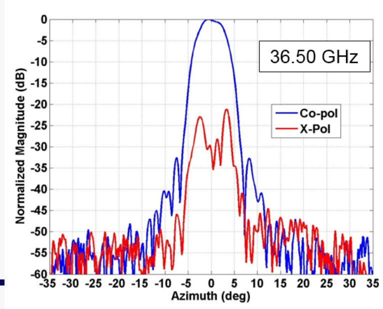
Laser radar used to ensure proper feed alignment.

WISM reflector antenna with WISM antenna feed

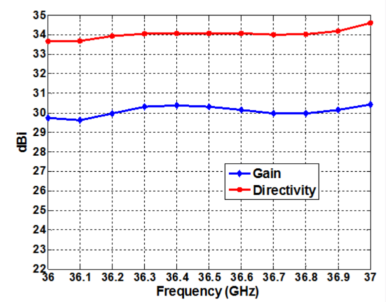


Primary reflector surface map, feed plane, and parent parabola; n_1 is the normal to the WISM reflector, centered at the vertex, and n_2 is the normal to the feed plane.

Principal Plane Pattern



Directivity and Gain



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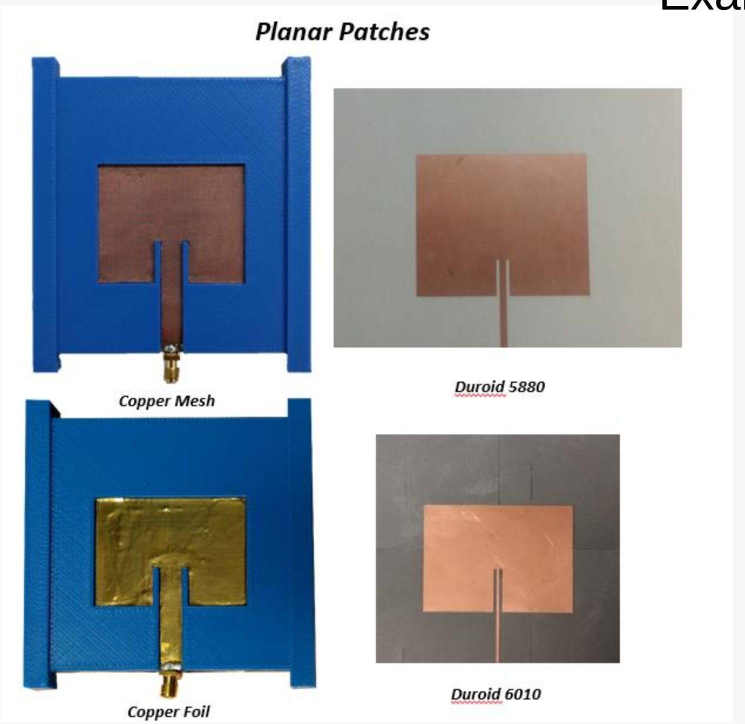
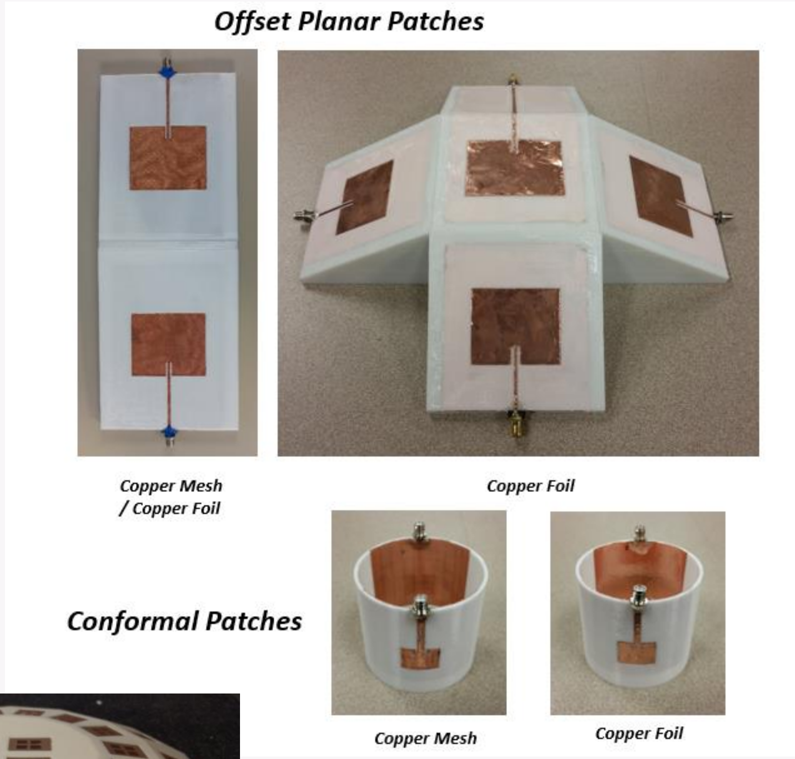
Ref: "Antenna Characterization for the Wideband Instrument for Snow Measurements," Kevin M. Lambert, Félix A. Miranda, Robert R. Romanofsky, Timothy E. Durham, and Kenneth J. Vanhille, 2015 International Symposium on Antennas and Propagation, July 19-25, 2015, Vancouver, CANADA

3D Printed Antennas for Cubesats/Smallsats Applications

Examples of Prototypes





Ka-Band (26 GHz) Switched Array 360^o Az 30^o El

GRC Collaborative effort with ASU, UTEP, UNM, and COSMIAC

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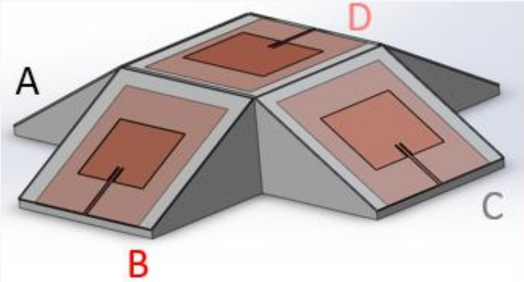
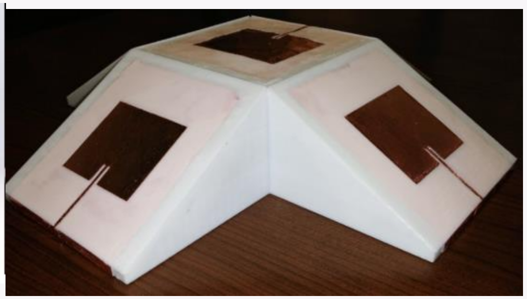
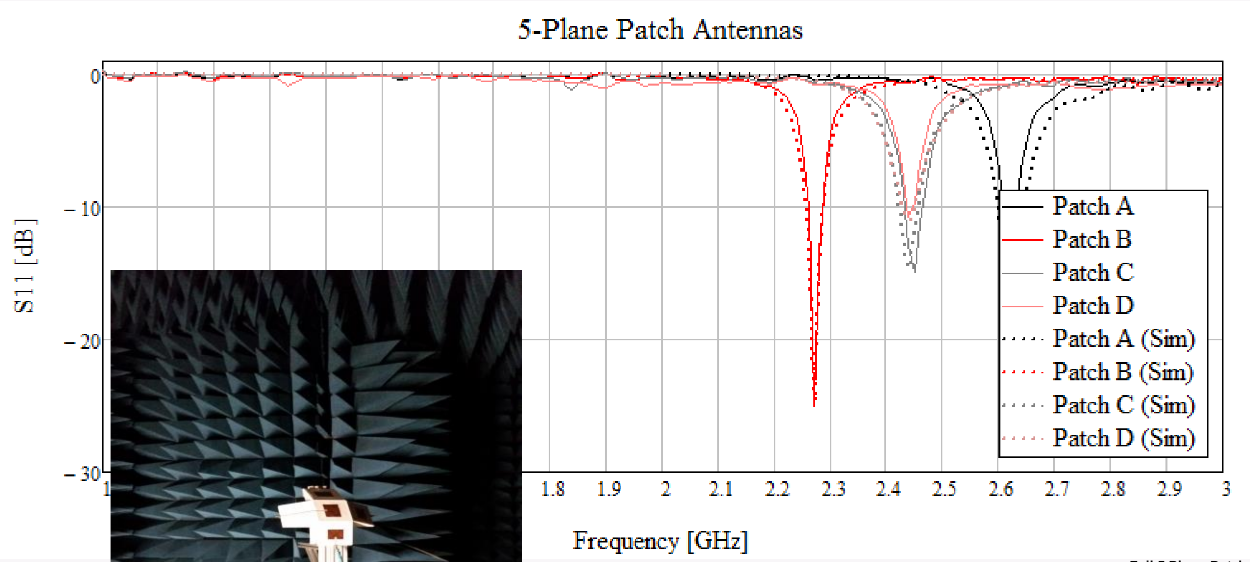
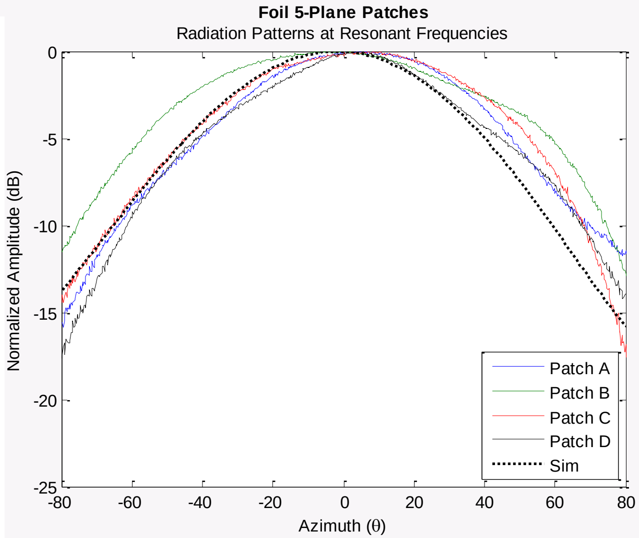
Measurement & Characterization



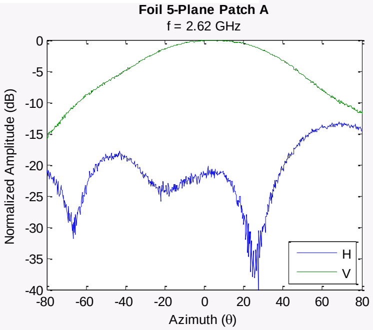


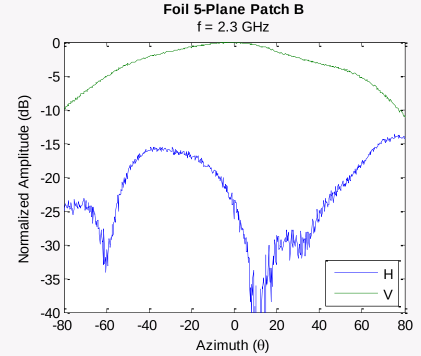
- Scattering Parameters / Return Loss
- Radiation Patterns
- Co- and Cross-Polarizations





Antenna in Far Field Range





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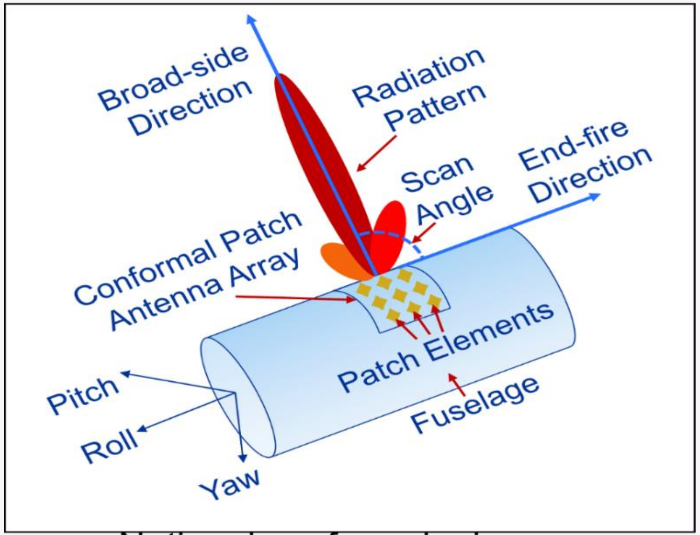
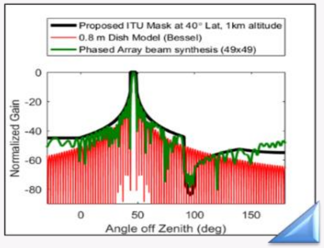
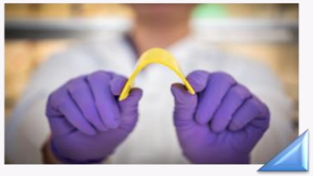
Low SWaP Conformal Antennas



Notional conformal microwave antenna with high EIRP

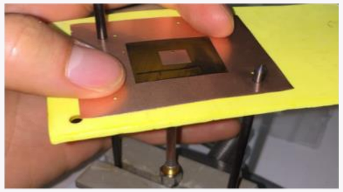


Challenge: Use phase array antenna beamforming to help mitigate ground station interference for ITU compliance

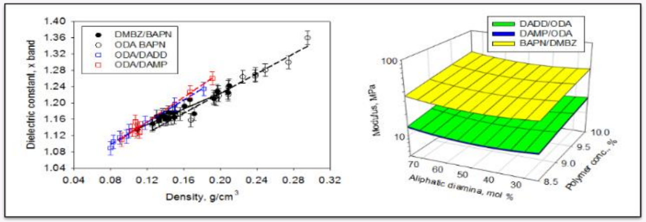


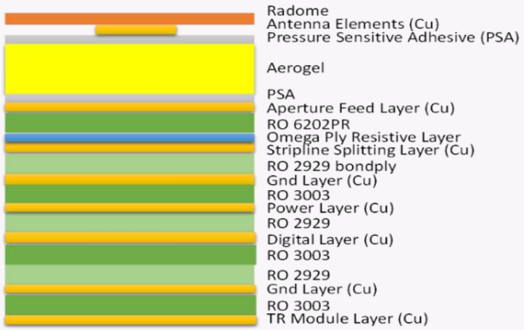
Challenge: Fabricate a tightly integrated antenna system using an ultra-lightweight flexible substrate

Goal: Advance technology for Ku-band phased array antenna using aerogel substrate to reduce SWaP (size weight and power) for UAV SatComm

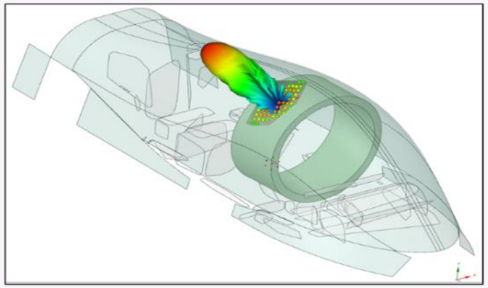


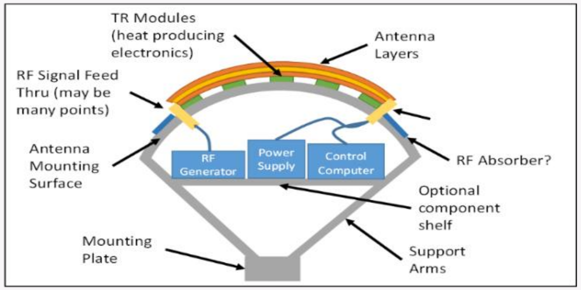
Single element antenna





Notional Antenna Design (not to scale)





Possible configurations for flight test of partial antenna array

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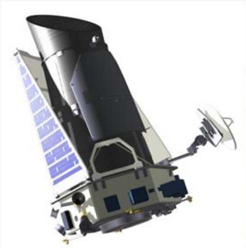
Power Amplifiers

High Power & Efficiency Space Traveling-Wave Tube Amplifiers (TWTAs) - A Huge Agency Success Story



LRO TWTA

SCaN Testbed TWTA

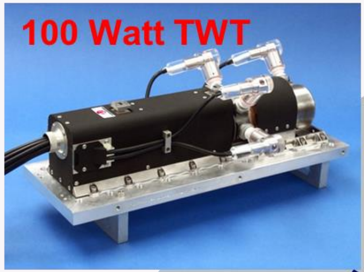
High Throughput

Q - V- & W-band TWTAs & Gbps Data Rates: 2012 & beyond

Lunar & ISS Missions: 2007-2011

- *Delivered K-band 40 W space TWTAs to the Lunar Reconnaissance Orbiter & CoNNeCT missions*

100 Watt TWT



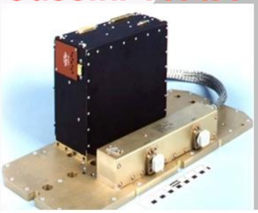
Jupiter Mission – Higher FoM: 2004-2006

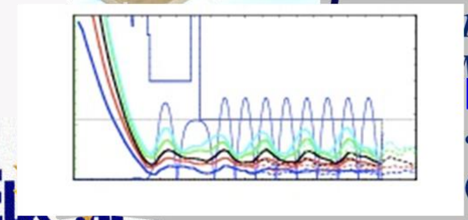
- *Space qualified a Ka-Band TWT, output power 200 W, efficiency 62 %, mass 1.5 kg. Output power 20X higher than Cassini TWT and FoM is 133*

Mars Mission – Higher Power & Efficiency: 2001-2003

- *Demonstrated a Ka-Band space TWT, output power 100 W, efficiency 60 %, mass 2.3 kg. Output power 10X higher than the Cassini TWT and FoM is 43*

Cassini TWTA



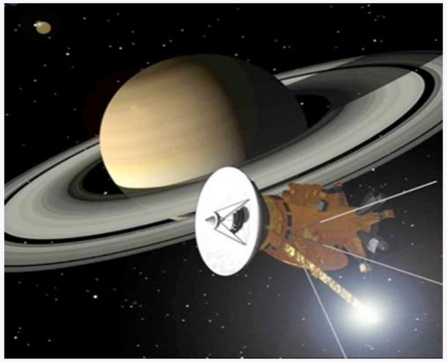


Cassini Mission: 1996-2000

- *Delivered a Ka-Band space TWT, output power 10 W, efficiency 41 %, mass 0.750 kg. Figure of Merit (FoM) is power/mass = 13*

Modeling & Simulations: 1980-1995

- *Basic design studies on traveling-wave tube (TWT) slow wave interaction circuits, collector circuit, focusing structure, electron gun and cathode*

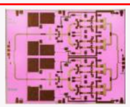


High Efficiency GaN MMIC Solid State Power Amplifiers for Satellite Communications

ADVANCES IN GaN HEMT TECHNOLOGY ENABLES LOW COST, LIGHT WEIGHT SSPAS FOR SATELLITE DOWNLINK APPLICATIONS

CURRENT STATUS

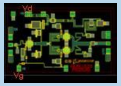
Ka TWTA
1500g



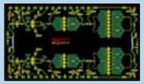
0.5 W GaAs pHEMT MMIC power amplifier
3.7 x 2.9 mm

- For 10 to 20 Watt power amplifiers (PAs) for downlink applications, TWTAs are heavy and costly.
- GaAs pHEMT SSPAs consume excessive power (~2X)

NEW INSIGHTS



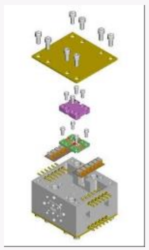
8W 2-20 GHz GaN MMIC PA
2.0 x 4.0 mm
(Analog Devices)



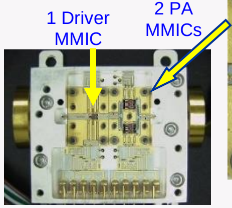
25W 6.0-12.0 GHz GaN MMIC PA
4.4 x 6.1 mm (CREE)

GaN HEMT technology achieves 4X higher power density than GaAs pHEMT with higher PAE.

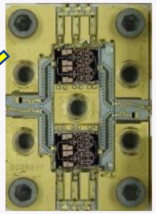
CURRENT WORK APPROACH



Exploded view (Identical bottom side)



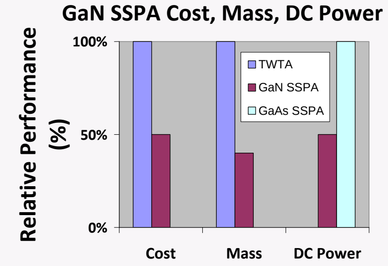
Module 50 x 50 x 25 mm; 100 grams combines 4 PA MMICs with 2 driver MMICs (identical bottom side)



Lange couplers or hybrids combine 2 PA MMICs in balanced configuration

- Develop a low cost, light weight, 10W X-band breadboard SSPA by integrating a 10W GaN PA MMIC along with driver amp MMIC
- Develop 20W X-band breadboard SSPA by power combining the output power from two GaN PA MMICs along with driver amp MMICs. Multiple power combining methods are available.

QUANTITATIVE IMPACT



- Compared to TWTA, >2X lower mass & cost
- Compared to GaAs pHEMT SSPA, 2X lower DC power

PROGRAM GOAL

- X-band 10W, 30% PAE SSPA breadboard module will integrate a 10W PA MMIC and driver MMIC in low cost light weight assembly
- Investigate the design, fabrication, and testing of Class-F Type of GaN PAs
- Investigate the design, fabrication, and testing of GaN Doherty PAs
- Using commercial foundry services fabricate GaN transistors for Ka-band PA MMICs

Effort funded by the SCaN Program

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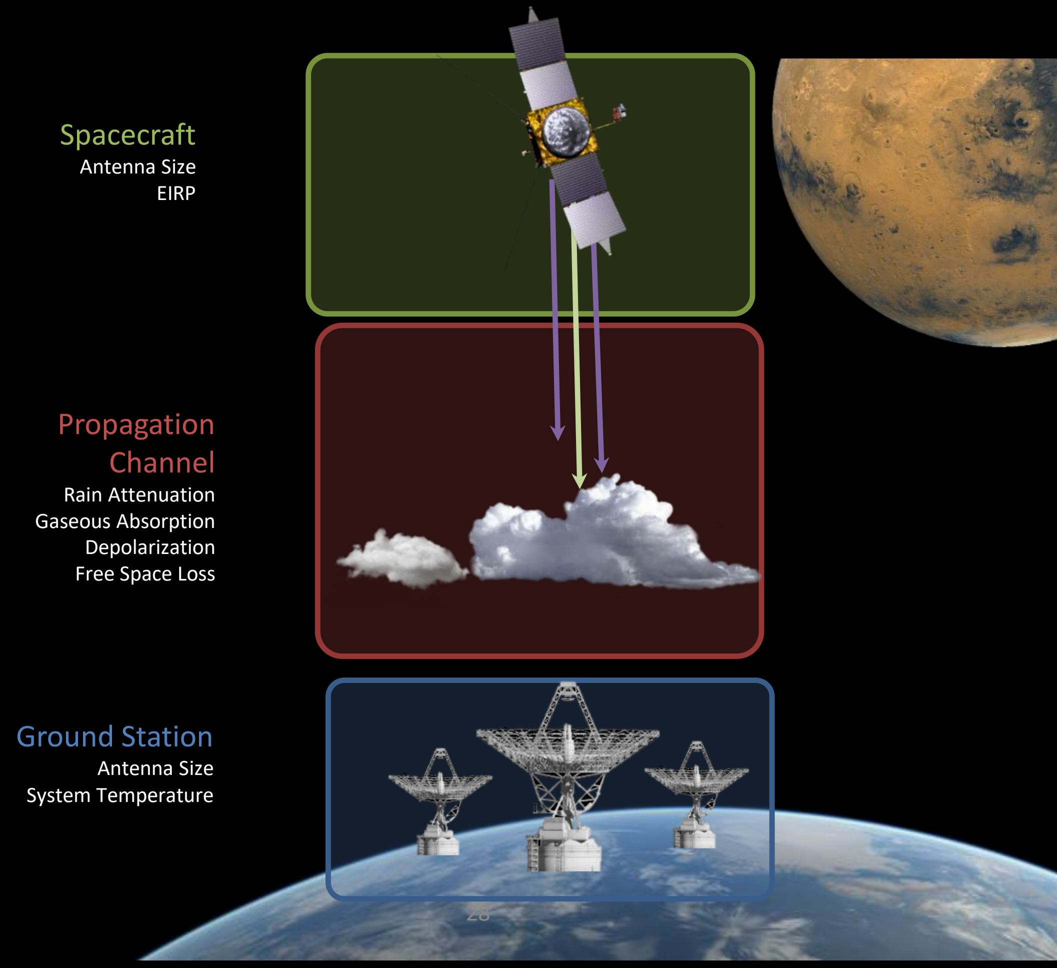
Atmospheric Propagation

It is well understood that the largest uncertainty in Earth-space communications system design lies in the impact of the stochastic atmospheric channel on propagating electromagnetic waves.

Proper characterization of the atmosphere is necessary to mitigate risk and reduce lifetime costs through the optimal design of the space and ground segment.

As NASA continues to move towards Ka-band operations (currently) and high data rate communications systems (future), the need for this data is becoming more and more critical to the development of reliable SATCOM systems.

Primary Objectives of Propagation Data Collection:
- **To reduce mission risk and mission costs by ensuring optimal design of SATCOM systems**
- **To minimize loss of mission critical data**

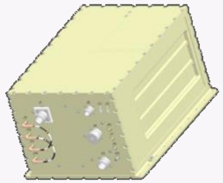


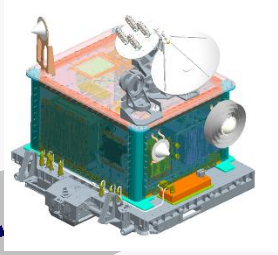
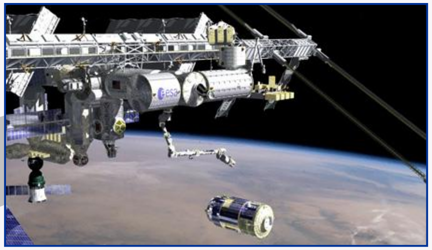
Atmospheric Propagation

Software Defined Radio and Cognitive Communications

Software Defined Radios-STRS Architectures

2010 – SCaN Testbed Flight Radios Developed by General Dynamics, Harris Corp., JPL

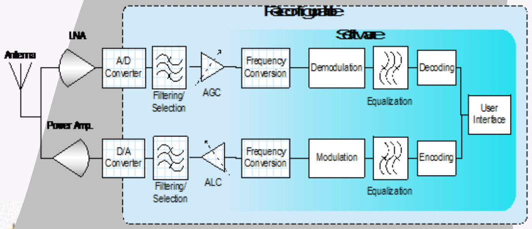



Technology Experiments: 2013 – 2018

Flight Technology Demonstration: 2008 – 2012
The Space Communications and Navigation (SCaN) Testbed (STB), established to perform system prototype demonstration in relevant environment (TRL-7). The STB was launched on July 12, 2012 to the ISS.

SDR Technology Development: 2005 – 2007
Development of design tools and validation test beds.
Development of design reference implementations and waveform components.
Establish SDR Technology Validation Laboratory at GRC.
NASA/Industry Workshops conducted

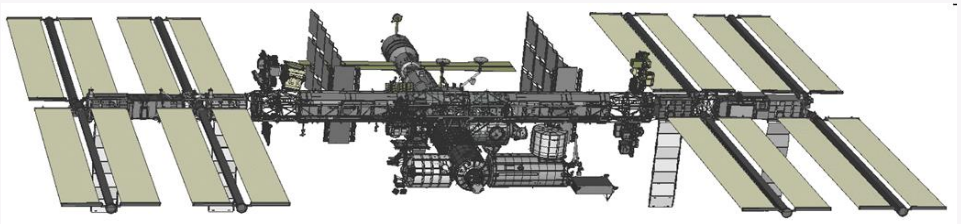


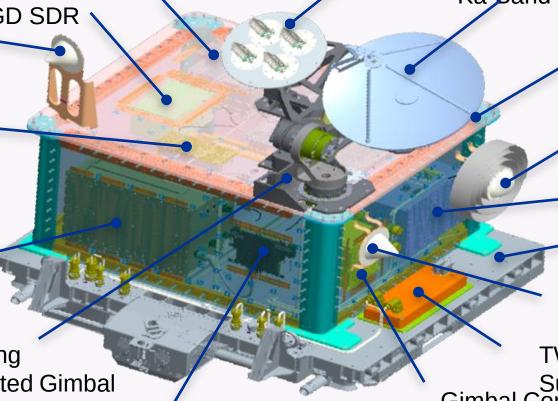
Open Architecture Development and Concept Formulation: 2002 – 2005
Develop common, open standard architecture for space-based software defined radio (SDR) known as Space Telecommunications Radio Architecture (STRS).
Allow reconfigurable communication and navigation functions implemented in software to provide capability to change radio use during mission or after launch.
NASA Multi-Center SDR Architecture Team formed.

Advancing the SOA in Software Defined Radios

GRC developed the **Scan Testbed (STB)** - launched to the ISS 2012

- Technology Demonstration Mission to mature Communication, Navigation, & Networking technologies for application in space
- Highly modular software enabling in-orbit reconfiguration and multi-waveform operation
- Coding and modulation can be varied based on link conditions resulting in improved performance and efficiency.
- To date over 20 Consultative Committee for Space Data Systems (CCSDS) Protocols including IP over CCSDS, Delay Tolerant Networking & Digital Video Broadcasting - Satellite - Second Generation (DVB-S2) have been implemented.





Since 2002, GRC has led development of the Space Telecommunications Radio System (STRS) architecture standard for SDRs. Standard allows waveforms to be reused for different applications and on platforms developed by different vendors.

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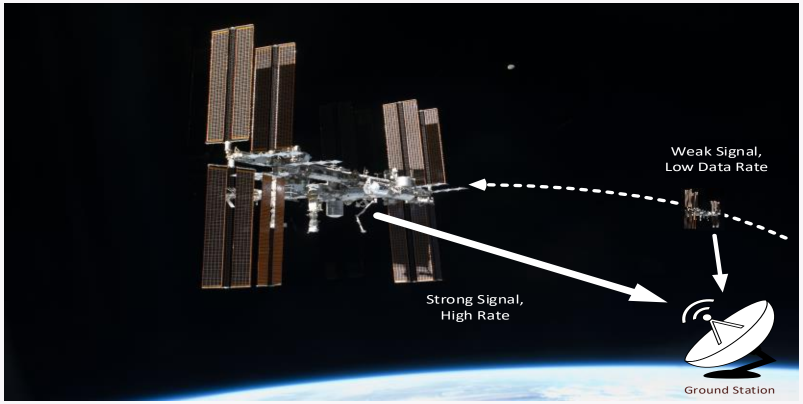
Roadmap to Cognitive Communications

Goal: Leverage STB and develop next generation cognitive technologies for communications to increase mission science return and improve resource efficiencies.

SCaN Test Bed is an early proving ground for experiments in cognitive communications

- ➢ Performed experiments in VCM and ACM
- ➢ Moving toward cognitive communications
    - More efficient use of spectrum, power and network resource management



Automatically compensate for dynamic link environment

SDR	Variable Coding & Modulation (VCM)	Adaptive Coding & Modulation (ACM)	Cognitive Radio/System
Configurable Properties	Reconfigure system based on predictions	Dynamic reconfiguration based on feedback	Adapting and learning to form intelligent systems: cognitive radios, intelligent networking, user initiated services, cognitive antennas

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Optical Communications

Why Optical Communications?

Depending on the mission , an optical communications solution could achieve…

- **~50% savings in mass**
  - **Reduced mass enables decreased spacecraft cost and/or increased science through more mass for the instruments**
- **~65% savings in power**
  - **Reduced power enables increased mission life and/or increased science measurements**
- **Up to 20-fold increase in data rate**
  - **Increased data rates enable increased data collection and reduced mission operations complexity**

…over existing RF solutions

Mars Reconnaissance Orbiter (MRO) Example

This image taken by the Mars Reconnaissance Orbiter represents what one could see from a helicopter ride at 1000 feet above the planet. While this mission is collecting some of the highest resolution images of Mars to date, bandwidth is still a bottleneck.

At MRO's maximum data rate of 6 Mbps (the highest of any Mars mission), it takes nearly 1.5 hours to transfer a single high-res image to earth.

In contrast, a 100 Mbps optical communications solution could transfer the image in less than 5 minutes.

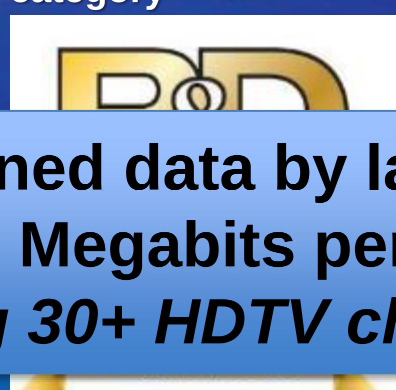
2013: NASA's First, Historic Lasercom Mission

The Lunar Laser Communication Demonstration (LLCD)

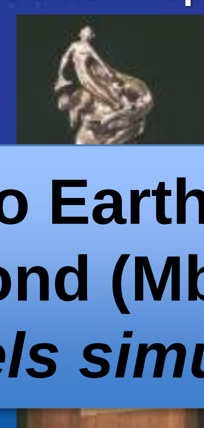
MIT Lincoln Laboratory, NASA GSFC, NASA Ames, NASA JPL, and ESA

2014 Popular Mechanics Breakthrough Award for Leadership and Innovation for LADEE

2014 R&D 100 Winning Technology in Communications category



Nominated for the National Aeronautic Association's Robert J. Collier Trophy



Winner of the National Space Club's Nelson P. Jackson Award for 2015

LLCD returned data by laser to Earth at a record 622 Megabits per second (Mbps)
= *streaming 30+ HDTV channels simultaneously!*

Laser Communication Relay Demonstration (LCRD) on STPSat-6 for June 2019 Launch

- Joint SCaN/NASA Space Tech Mission
- Hosted payload with AFRL/STP
- Two to eight years of mission ops
- Flight Payload (NASA Goddard)
  - Two LLCD-heritage Optical Modules and Controller Electronics Modules
  - Two software-defined DPSK Modems with 2.88 Gbps data rate (1.244 Gbps user rate)
  - 622 Mbps Ka-band RF downlink
  - New High Speed Switching Unit to interconnect the three terminals
  - RFI for "Guest Investigators" revealed significant commercial interest
- Key for NASA's Next-Gen Earth Relay in 2024 timeframe

37

Integrated Radio and Optical Communications

Revolutionary Capability in an Evolutionary Manner

Objectives:

- Combine the best features of select deep space RF and optical communications elements into an integrated system
- Realize Ka-Band RF and 1550 namometer optical capability within MRO payload envelope
- Prototype and demonstrate performance of key components to increase TRL, leading to integrated hybrid communications systems demonstration

Relevance/Findings:

- Enables new capabilities: 44 X greater instantaneous data rate over MRO X-band system from optical portion of IROC; 17 X greater instantaneous data rate over MRO X-band system from RF portion of IROC. RF and Optical can be combined if power is available, for 61X improvement. Additional contact time from Mars of 20 to 25 days per year over an all-optical beacon-based system.
- Reduces mission risk for transition to optical comm technology by integrating with highly capable and robust RF system
- Operates without requirement for uplink laser beacon
- Provides extensible system design beyond Martian distances

Key enabling technologies recommended for integration:

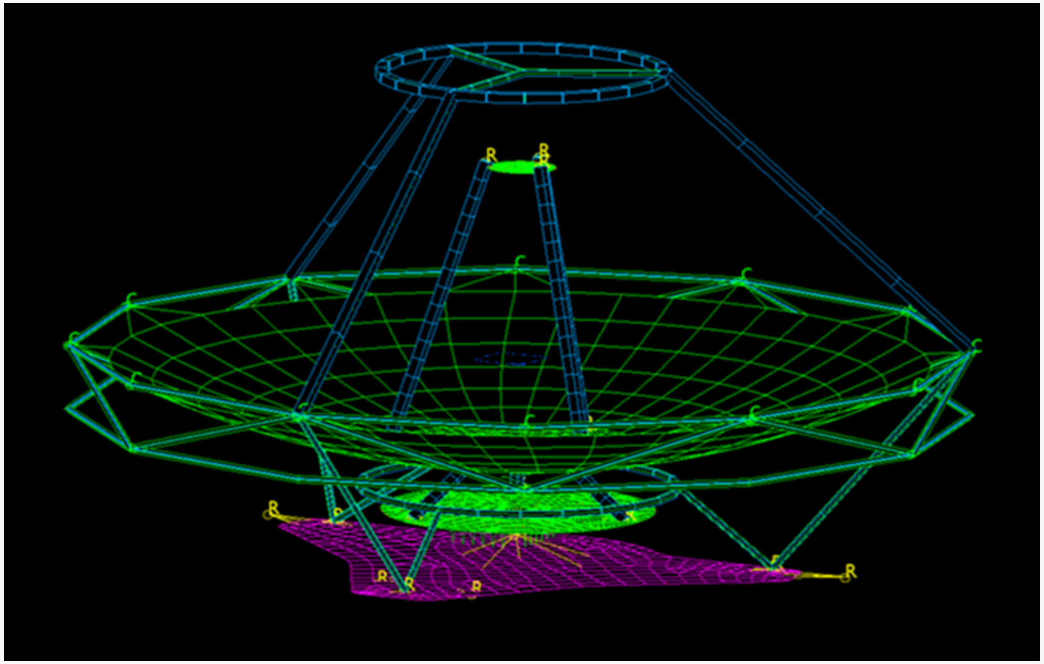
- Precision (2 micro-radian) autonomous pointing
- Combined RF/optical Teletenna
- RF/optical Software Defined Radio (SDR)
- Networked RF/optical link management

Co-Principal Investigators:

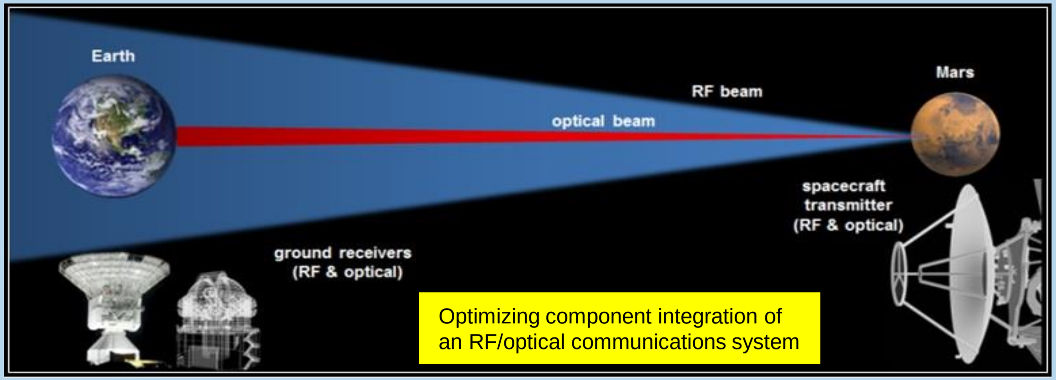
- Dr. Robert Romanofsky and Dr. Scott Sands

Project Manager:

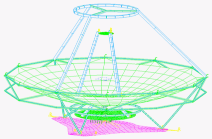
- Thomas Kacpura



Lightweight 3-meter Ka-Band Mesh/25 cm Optical Composite Mirror Teletenna Subsystem

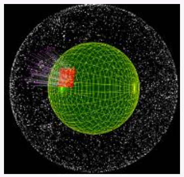


iROC--Focusing on 4 Key Enabling Technology Areas Recommended for Hybrid RF & Optical Communications



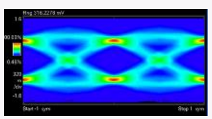
Combined RF/optical Teletenna

- Co-boresighting simplifies comm payload integration with spacecraft
- Maximizes line of sight availability between aperture and earth



Precision beaconless pointing / navigation through sensor fusion

- Increases spacecraft autonomy and capability
- Permits flexibility in telescope aperture selection (i.e. no minimum aperture size required to detect dim beacon)
- Uplink beacons will be challenging to implement and operate in locations where high speed ground infrastructure is located



RF/optical Software Defined Radio (SDR)

- Provides reconfigurability for evolving mission requirements and developing infrastructure

Networked RF/optical link management

- Enables automation of the system, transparent to the user
- Provides quality of service and security
- Utilizes network nodes in an optimal manner

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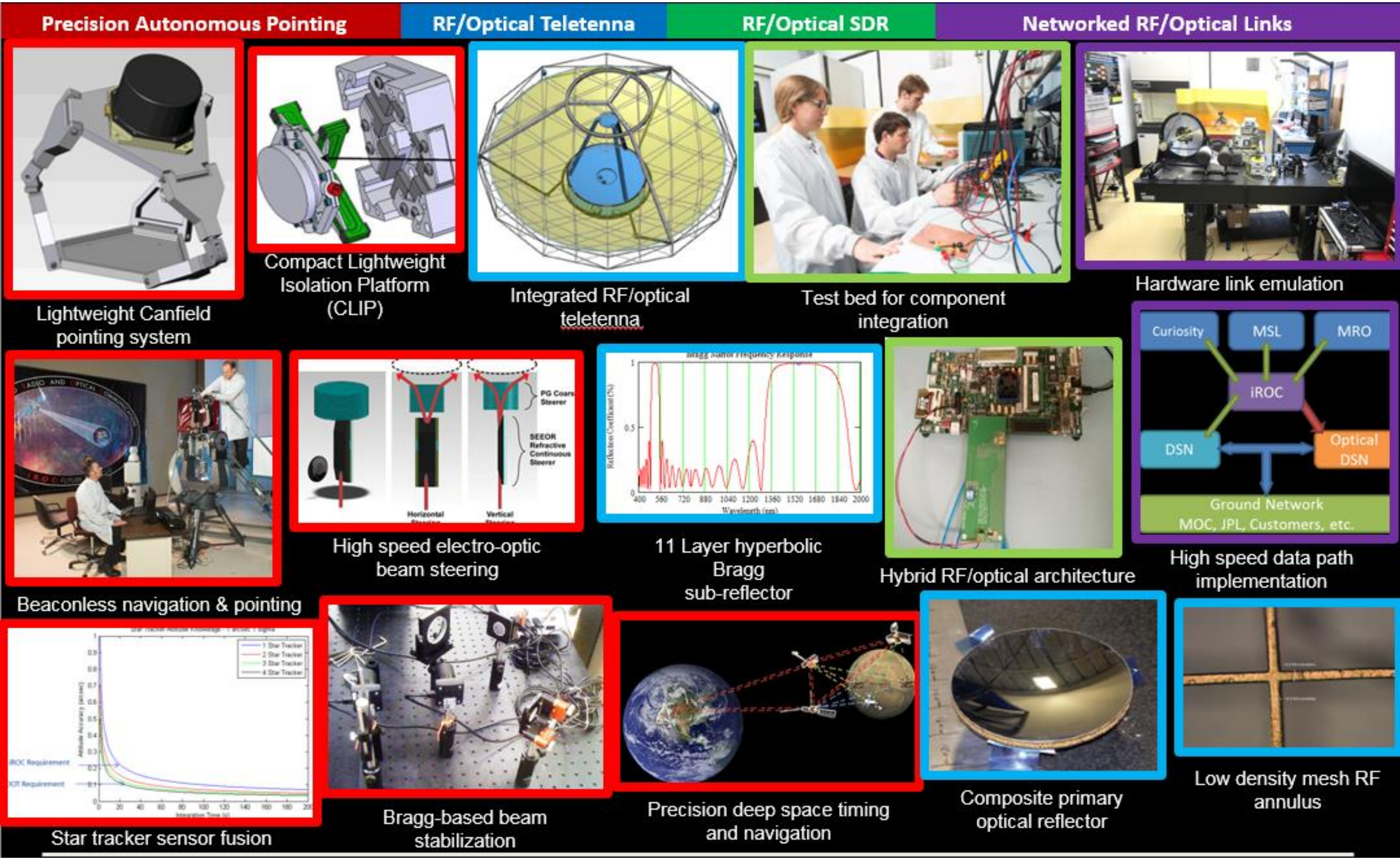
Combining RF & optical for minimal SWaP

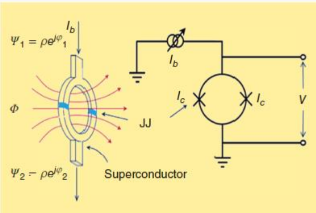
The iROC Team is Developing Several Valuable Technologies to Enable Next Generation Optical and RF Communications



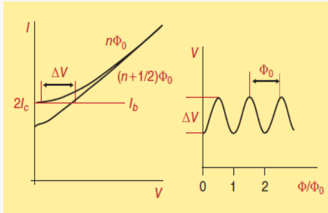
Disruptive Technologies

Superconducting Quantum Interference Filter (SQIF)

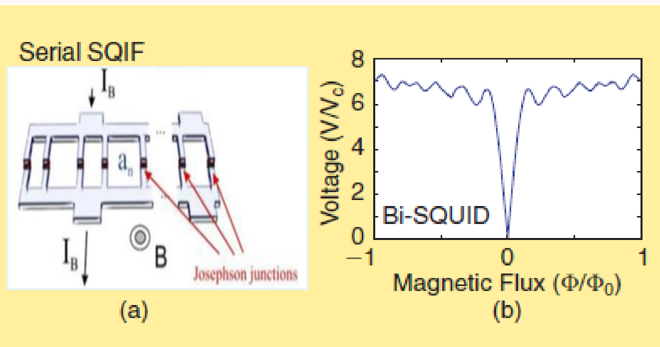
Operating Principles



A single SQUID

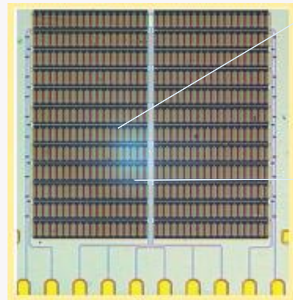


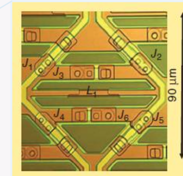
Periodic flux-to-voltage response



- SQUID voltage response is periodic in the applied magnetic field
- SQIF is an array of SQUIDs of incommensurate area with a unique magnetic flux-to-voltage response
- Sensitivity improves with arraying more SQUID cells (S/N ~ $\sqrt{N}$)

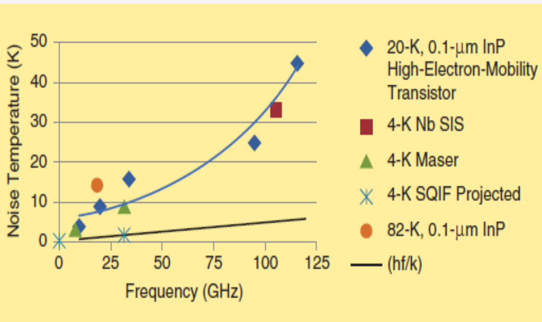
Integrated circuit of 2-D SQIF arrays



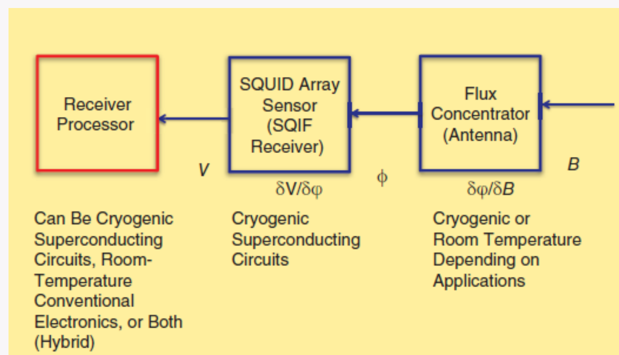


HYPRES Nb 2-D bi-SQIF array

Comparative Technologies



SQIF receiver conceptual block diagram



- Energy sensitivity of about 10^{-31} J/Hz, compared to semiconductor 10^{-22} J
- Sensitivity approaches quantum limit, while increasing dynamic range and linearity
- Attractive for wideband-sensitive receivers
- Robust to variation in fabrication spread (e.g. junction critical current, inductance, etc.)

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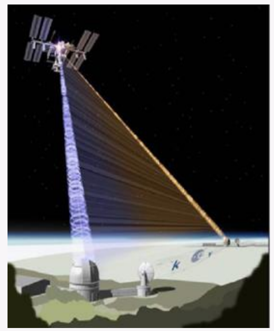
QUANTUM COMMUNICATIONS AND QUANTUM KEY DISTRIBUTION

Motivation

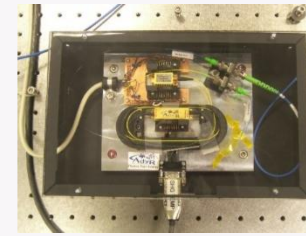
- Current secure communication algorithms rely upon computationally difficult problems, such as finding prime factors of very large integers, to maintain secrecy.
- These algorithms will be ineffective when a practical quantum computer is developed as it would readily solve computationally difficult problems.
- ***Solution*:** Quantum Key Distribution (QKD) which enables unconditionally secure communication.



Proposed ISS Experiment
[source: Armengol,2008]

Quantum Entanglement

- Einstein, Podolsky, and Rosen (1935) *: **If quantum mechanics is correct, two particles could be linked (entangled) such that a measurement of one would affect both it and its partner instantaneously – "spooky action at a distance".***
- Two photons share a quantum state so that the measurement of one affects the other - experimentally demonstrated by Aspect (1981).



High intensity source of entangled photons

Technology Description

- An important potential application of quantum communications is for QKD to provide unconditionally secure satellite communications.
- In QKD, a coding 'key' is established by transmitting one quantum entangled photon to the receiver and one is measured by the sender. If a third party observes the transmitted photon, the observation will change the state of the entangled pair (because of the Heisenberg uncertainty principle) and both the sender and receiver will be able to determine that the key has been intercepted.
- Once it is known that the key has not been observed, the key is used to code a message which is then sent over a conventional (public) communications channel as the security of the key is absolutely certain.

GRC Goals

- **Our goal is to establish a quantum communications link and eventual network between Earth and low earth orbit (LEO).**
- Link budget analysis indicates that a small percentage of photons transmitted from Earth will be detected at LEO.
- Therefore a source to provide high quality entangled photons at a high rate is needed.
- NASA has funded AdvR, Inc to develop a high rate entangled photon source with a potassium titanyl phosphate (KTP) waveguide approach which GRC is using to test QKD protocols.

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Summary

The specific communications technologies needed for future NASA exploration missions to ensure full availability of deep space science mission data returns will depend on:

- Data rate requirements, available frequencies, available space and power, and desired asset-specific services. Likewise, efficiency, power, mass, and cost will drive decisions.
- As the RF spectrum becomes increasingly congested there is a need to move to higher frequencies (e.g., upper Ka-Band and 5G) and to develop technologies (e.g., cognitive radios, cognitive antennas, memristors, etc.) as well as algorithms to enable cognitive communications systems resulting on efficient spectrum utilization.
- The optical spectrum is essentially wide open and we are in the midst of "Decade of Light" where new space communications architectures will have optical communications as an integral part.

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